Outline

1. Tropical Cyclone Climatology
2. Methods for Assessing TC Wind Hazard
3. Baselines for Present and Future TC Wind Hazard
4. Moving from Hazard to Risk: The Hurricane Risk Calculator
1. Tropical Cyclone Climatology

• Definition
• Conditions for genesis
• Distribution (time, space, seasonality)
• Variability (interannual, interdecadal)
WMO Definition of a Tropical Cyclone

“A warm-core, non-frontal synoptic-scale cyclone, originating over tropical or subtropical waters, with organized deep convection and closed surface wind circulation about a well-defined center.”
Breaking down the WMO definition

- **warm-core**
- **non-frontal**
- **synoptic-scale cyclone (low pressure)**
- **originating over tropical or subtropical waters**
- **organized deep convection**
- **closed surface wind circulation about a well-defined center**

**Notes:**
- No intensity criterion is listed
- Origination over water is a key, as it implies that the cyclone derives its energy from the surface fluxes.
Conditions for Genesis

• “We observe universally that tropical storms form only within pre-existing disturbances...An initial disturbance therefore forms part of the starting mechanism. A weak circulation low pressure and a deep moist layer are present at the beginning. The forecaster need not look into areas which contain no such circulations.”

Herbert Riehl (1954)
Distribution of Genesis

TC genesis locations from 1949-2006 (Northern Hemisphere)

From RAMMB Tropical Cyclone Genesis Project
Large-Scale Conditions and Other Characteristics Associated with TC Formation

**Necessary but not sufficient conditions!**  
(Gray 1968, 1975)

- A pre-existing disturbance containing abundant deep convection
- Latitudes poleward of ~5º
- Adequate ocean thermal energy 
  \[ \text{SST} > 26^\circ \text{C} \text{ extending to a depth of 60 m} \]
- A “sufficiently” conditionally unstable atmosphere
- Enhanced mid-tropospheric relative humidity (700 hPa)
- Weak vertical shear of the horizontal wind

NHC and COMET
Time Series of TC Genesis Parameters (2012)

- Trop All Vertical Shear (Curr) vs. (Clim)
- Trop All Vertical Instability (Curr) vs. (Clim)
- Trop All 950 hPa Circulation (Curr) vs. (Clim)
- Trop All 850 hPa Circulation (Curr) vs. (Clim)
- Trop All 24 hr Formation Probability (Curr) vs. (Clim)
- Total 24 hr Formation Probability (%) vs. (Current vs. Clim)
Tropical Cyclone Average Seasonal Cycles

North Atlantic (1886-1989)
- Average Number of Days per Season with Tropical Cyclone Winds
  - $\geq 34$ knots: 59
  - $\geq 64$ knots: 27

Eastern & Central North Pacific (1966-1989)
- Average Number of Days per Season with Tropical Cyclone Winds
  - $\geq 34$ knots: 83
  - $\geq 64$ knots: 34

North Indian (1891-1989)
- Average Number of Days per Season with Tropical Cyclone Winds
  - $\geq 34$ knots: 16
  - $\geq 64$ knots: 3

Western North Pacific (1945-1988)
- Average Number of Days per Season with Tropical Cyclone Winds
  - $\geq 34$ knots: 154
  - $\geq 64$ knots: 80

Australia/S. Pacific/SE Indian (1958-1988)
- Average Number of Days per Season with Tropical Cyclone Winds
  - $\geq 34$ knots: 36
  - $\geq 64$ knots: 11

Southwest Indian (1947-1988)
- Average Number of Days per Season with Tropical Cyclone Winds
  - $\geq 34$ knots: 65
  - $\geq 64$ knots: 21

NOAA/NWS/NHC
Sources of Disturbances

• African Easterly Waves
• Intertropical Convergence Zone (ITCZ)
• Equatorial Waves and Madden Julian Oscillation (MJO)
• Tropical Upper Tropospheric Trough (TUTT)
• Monsoon Trough

Specifics of the disturbance might not be that important. Genesis may behave like a stochastic process.
Large-Scale Conditions Associated with TC Formation

- Upper-tropospheric anticyclonic outflow over the area
- Enhanced lower tropospheric relative vorticity
- Appearance of curved banding features in the deep convection
- Falling surface pressure: 24-hour pressure changes (falls) of usually 3 mb or more
Principal Areas of Tropical Cyclones

Tropical Cyclones, 1945–2006

Saffir-Simpson Hurricane Scale:
August

[Map showing hurricane tracks with Likely, More Likely, Most Likely categories.]
September
October
November
Long-term Variability

Atlantic Basin Storm Count
(Including Subtropical Cyclones)

Number of Systems

Year

Data Source: NHC
Saffir-Simpson Hurricane Wind Scale

• A “scale using 1 to 5 categorization based on a hurricane’s intensity at the indicated time. The scale provides examples of the type of damage and impacts associated with each indicated intensity. In general, damage rises by a factor of four for every category increase.” (NWS 2017; Simpson 1974). The sustained wind thresholds for the categories are as follows for various units:

<table>
<thead>
<tr>
<th>Category</th>
<th>mph</th>
<th>knots</th>
<th>m s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>74-95</td>
<td>64-82</td>
<td>33 to 42</td>
</tr>
<tr>
<td>2</td>
<td>96-110</td>
<td>83-95</td>
<td>43 to 49</td>
</tr>
<tr>
<td>3</td>
<td>111-129</td>
<td>96-112</td>
<td>50 to 57</td>
</tr>
<tr>
<td>4</td>
<td>130-156</td>
<td>113-136</td>
<td>58 to 70</td>
</tr>
<tr>
<td>5</td>
<td>&gt;156</td>
<td>&gt;136</td>
<td>&gt; 70 m s⁻¹</td>
</tr>
</tbody>
</table>
Long Term Variability

Interannual influences
• North Atlantic Oscillation (NAO)
• El Niño and La Niña

Interdecadal influences
• Atlantic Multidecadal Oscillation (AMO)
• Pacific Decadal Oscillation (PDO)
• Thermohaline Circulation changes
2. Methods of Assessing TC Wind Hazard

• Local method / statistical modeling
• Synthetic track modeling

Goal is to characterize the long-term hazard posed by tropical cyclones
Local / Statistical Methods

Count # of TCs crossing coast in a particular region, then determine the long-term average

Advantages:

- Can be quite accurate on the large scale when there are sufficient high quality records

Drawbacks:

- Requires a consistent long-term record
- There may not be any landfalls during the historical period, even though TCs are physically plausible in that region
- Rare events may not be captured
- **Sampling errors** may result from chance clustering of landfalls, lack of landfalls in other areas
Tropical Cyclone Tracks
Data from 1949 in the Pacific, from 1851 in the Atlantic

All North Atlantic and Eastern North Pacific tropical cyclones (from Ethan Gibney, NHC/WFO SGX)
Total number of hurricane strikes by counties/parishes/boroughs, 1900-2010

Note: When comparing values for counties/parishes/boroughs, differences in geographical size should be considered.

Total number of major hurricane strikes by counties/parishes/boroughs, 1900-2010


Note: When comparing values for counties/parishes/boroughs, differences in geographical size should be considered.
More sophisticated statistical approaches

• TC landfalls are modeled as a random Poisson process (e.g., Parisi and Lund 2008)
• A model is created using various covariates (e.g., ENSO, NAO)
• When the model can sufficiently represent observed TC landfall rates, it can be used to answer questions about the expected landfall rates at various intensities

Advantages:
• Return periods can be explicitly estimated
  ▪ Expected (average) time that one must wait until a hurricane with \( w \) or greater wind speed makes landfall in the region of interest
Synthetic track modeling

Historical database is selected

The following parameters are assessed:

- Long-term genesis rates
- Track characteristics (direction, speed)
- Intensity characteristics

Kernel density functions are created to represent the spatial variation of these quantities
Many Different Databases
Kernel density function of genesis

Fig. 12 of Hall and Jewson 2007
Generation of Synthetic Tracks

- The kernel density functions are randomly sampled to draw out the parameters that are used to determine the genesis location.

- An auto-regressive (lag-1 autocorrelation) model is typically used:
  - statistics of track characteristics (e.g., displacements) are drawn for that region.
  - track is constructed using some information about the previous displacement to have some consistency.
  - track is usually assumed to be independent of intensity.
Comparison of synthetic tracks

Observed\textsubscript{(historical)}

simulated

simulated

simulated

Fig. 14 of Hall and Jewson 2007
Track density

Fig. 15 of Hall and Jewson 2007
Event Sets

• Once a suitable event set has been generated (e.g., 1000, 5000, or even 100,000 simulated years), all sorts of statistics can be computed directly

  ▪ Return periods for a ‘strike’ by a TC of a given intensity in a given period
  ▪ Clustering -- return periods for multiple TCs of a given intensity threshold
  ▪ Crossing rates for a given region
Landfall crossing rates

Fig. 14 of Hall and Jewson 2007
Addition of Parametric Wind Models

- A parametric wind model is a simple way to represent the wind field of a TC.
Statistical-Parametric Models

• Use of a parametric wind model with the synthetic track approaches allows one to assess the wind hazard at any given point
• Record maximum winds from each event
• Fit to an extreme value distribution (e.g., Pareto)
• Compute return periods, return levels
Some questions

• How well do the synthetic tracks really do in capturing the local variations in TC tracks?
• Are there other dynamical or environmental effects that are important?
• Is the assumption that intensity is independent of track really a good assumption?
• How do the wind change inland?
All North Atlantic and Eastern North Pacific tropical cyclones (from Ethan Gibney, NHC/WFO SGX)
All North Atlantic and Eastern North Pacific tropical cyclones (from Ethan Gibney, NHC/WFO SGX)
Approaches used to examine future changes

• Statistical Downscaling
  ▪ Use Genesis Potential based on large-scale conditions to estimate genesis rates in future climate
  ▪ Advantages:
    • Inexpensive
  ▪ Disadvantages:
    • Does not say anything about what happens after genesis
Approaches used to examine future changes, cont’d

• **General Circulation Models (GCMs)**
  - GCMs are too coarse to adequately represent TC inner core processes
  - Cannot represent intense TCs
  - Statistical approaches such as quantile-quantile mapping or extreme value analysis may be used, but there are many potential issues
    - SST bias off west coast of Mexico
    - Vertical wind shear bias in tropical Atlantic
  - GCMs can still be useful to inform on the large-scale trends such as potential intensity
Approaches used to examine future changes, cont’d

• **Dynamical Downscaling**
  - Involves running a higher resolution full-physics model using the GCM boundary conditions
  - Examples: GFDL hurricane model
  - Tropical channel alternative
  - **Advantages:**
    - Represents inner core dynamics better than any other method
    - Can represent intense TCs
  - **Disadvantages:**
    - Extremely expensive
    - Typically cannot simulate a long climate period
    - Questions about the boundaries
Deterministic Downscaling (Emanuel method)

- Uses a database of synthetic tracks
- Disturbances are “seeded” and a simple axisymmetric intensity model is run
- The disturbances that grow are considered TCs

**Advantages:**
- Can represent intense TCs much better than GCMs
- TC intensities are consistent with the large scale environment simulated by the GCM (potential intensity, vertical shear)

**Disadvantages:**
- Still subject to assumptions about the seeding rate of disturbances
- If actual genesis rate decreases, may overpredict intense TCs
IPCC Statement on TC Intensity

• Global mean TC maximum wind speed is likely to increase.

• “Improvements in model resolution and downscaling techniques increase confidence in projections in intense storms, and the frequency of the most intense storms will more likely than not increase substantially in some basins.”

• “The available modeling studies that are capable of producing very strong cyclones typically project substantial increases in the frequency of the most intense cyclones and it is more likely than not that this increase will be larger than 10% in some basins.” 
IPCC Statement on TC Frequency

• “Based on process understanding and agreement in 21st century projections, it is *likely* that the global frequency of occurrence of tropical cyclones will either decrease or remain essentially unchanged . . . The future influence of climate change on tropical cyclones is *likely* to vary by region, but the specific characteristics of the changes are not yet well quantified and there is *low confidence* in region-specific projections of frequency and intensity.”
3. Baselines for Present and Future TC Wind Hazard

**Goal:** Quantitatively assess changing wind hazard due to a set assumption on how TC intensity will react to intensity change

**Approach:**
- Use recent 30-year historical records
- Fill in missing central pressures using a wind-pressure relationship
- Run Australia Geoscience Tropical Cyclone Risk Model (TCRM) for current climate (1986-2015)
- Assume that intensity increases 10% across the board for all TCs at all times in the 2071-2100 climate (e.g., RCP8.5)
- Run TCRM for future climate to get new return periods, etc.
Global Distribution of Tropical Cyclones (1986-2015)

Intensity (maximum 1-minute wind speed)  Historical Observations
Global Distribution of Tropical Cyclones (1986-2015)

Minimum Sea Level Pressure  Historical Observations

Legend
- Red: mslp < 920 hPa
- Orange: 920 hPa < mslp ≥ 944 hPa
- Yellow: 944 hPa < mslp ≥ 965 hPa
- Green: 965 hPa < mslp ≥ 980 hPa
- Blue: 980 hPa < mslp ≥ 995 hPa
- Light Blue: 995 hPa < mslp ≥ 1005 hPa
- Blue: mslp > 1005 hPa
- Black: Missing

This plot uses data obtained from National Hurricane Center and Joint Typhoon Warning Center best tracks.
Global Distribution of Tropical Cyclones (1986-2015)

Environmental Pressure  Historical Observations

Legend
- penv < 995 hPa
- 995 hPa < penv ≤ 1000 hPa
- 1000 hPa < penv ≤ 1005 hPa
- 1005 hPa < penv ≤ 1010 hPa
- 1010 hPa < penv ≤ 1015 hPa
- 1015 hPa < penv ≤ 1020 hPa
- penv > 1020 hPa
- Missing

This plot uses data obtained from National Hurricane Center and Joint Typhoon Warning Center best tracks.
Global Distribution of Tropical Cyclones (1986-2015)

Central Pressure Deficit (Δp)    Historical Observations

Legend
- Δp ≥ 95 hPa
- 95 hPa < Δp ≤ 71 hPa
- 71 hPa < Δp ≤ 50 hPa
- 50 hPa < Δp ≤ 35 hPa
- 35 hPa < Δp ≤ 20 hPa
- 20 hPa < Δp ≤ 10 hPa
- Δp < 10 hPa
- Missing

This plot uses data obtained from National Hurricane Center and Joint Typhoon Warning Center best tracks.
Global Distribution of Tropical Cyclones (1986-2015)

Radius of Maximum Wind (nm)  Historical Observations

This plot uses data obtained from National Hurricane Center and Joint Typhoon Warning Center best tracks.

Legend
- Heavy: RMW > 40 nm
- Large: (25 nm ≤ RMW < 40 nm)
- Normal: (12 nm ≤ RMW < 25 nm)
- Small: (5 nm ≤ RMW < 12 nm)
- Tiny: (RMW < 5 nm)
- Tropical Storm
- Tropical Depression
- Missing RMW

Radius of maximum wind values are only shown for tropical cyclones with intensity >= 34 kt.
Global Distribution of Tropical Cyclones (1986-2015)

Radius of Maximum Wind (nm)  Historical Observations

Legend
- Red: RMW > 60 nm
- Orange: 25 nm < RMW < 60 nm
- Yellow: 12 nm < RMW < 25 nm
- Green: 5 nm < RMW < 12 nm
- Blue: RMW = 5 nm
- Light Blue: Tropical Storm
- Grey: Tropical Depression
- Black: Missing RMW

This plot uses data obtained from National Hurricane Center and Joint Typhoon Warning Center best tracks. Radius of maximum wind values are only shown for tropical cyclones with intensity >= 54 kt.
Wind-Pressure Relationship for Global Tropical Cyclones (1986-2015)

Vmax vs. Pressure (original MSLP values from b-deck)

Historical Observations

MSLP (mb)

Vmax$_{1\text{-min}}$ (kt)
Wind-Pressure Relationship for Global Tropical Cyclones (2071-2100)

Vmax vs. Pressure  
Future Scenario: Intensity increases 10% by 2100  
(C-K WPR used to fill in missing MSLP values)
Global Distribution of Tropical Cyclones (1986-2015)

Intensity (maximum 1-minute wind speed)  Historical Observations
Global Distribution of Tropical Cyclones (2071-2100)

Intensity (maximum 1-minute wind speed)  Future Scenario: Intensity increases 10% by 2100

This plot uses data obtained from National Hurricane Center and Joint Typhoon Warning Center best tracks.
10-yr Return Level Windspeed

Period: 1986-2015
tcwind v0 hist-rcp85

Return Level 3-sec Wind Gust (kt) for the 10-year Return Period
Category 3 Risk

Period: 1986-2015
tcwind v0 hist-rcp85

\[ V_{\text{max, 3-sec}} \geq 118 \text{ kt} \]

Return Period of a 3-sec Wind Gust \( \geq 118 \text{ kt} \)
Tropical Storm Risk (storm-force)

Period: 1986-2015
tcwind v0 hist-rcp85

$V_{\text{max}, \text{3-sec}} \geq 62 \text{ kt}$

Annual Exceedance Probability of a 3-sec Wind Gust $\geq 62 \text{ kt}$
Category 1 Risk

Period: 1986-2015
tcwind v0 hist-rcp85

$V_{\text{max, 3-sec}} \geq 79 \text{ kt}$

Annual Exceedance Probability of a 3-sec Wind Gust $\geq 79 \text{ kt}$
Category 2 Risk

Period: 1986-2015
tcwind v0 hist-rcp85

$V_{\text{max}, \text{3-sec}} \geq 102 \text{ kt}$

Annual Exceedance Probability of a 3-sec Wind Gust $\geq 102$ kt
Category 3 Risk

Period: 1986-2015

tcwind v0 hist-rcp85

$V_{\text{max, 3-sec}} \geq 118 \text{ kt}$

Annual Exceedance Probability of a 3-sec Wind Gust $\geq 118 \text{ kt}$
Category 4 Risk

Period: 1986-2015
tcwind v0 hist-rcp85

$V_{\text{max, 3-sec}} \geq 139 \text{ kt}$

Annual Exceedance Probability of a 3-sec Wind Gust $\geq 139 \text{ kt}$
Category "6" Risk

Period: 1986-2015

tcwind v0 hist-rcp85

\[ V_{\text{max, 3-sec}} \geq 192 \text{ kt} \]

Annual Exceedance Probability of a 3-sec Wind Gust \( \geq 192 \text{ kt} \)
Category "7" Risk

Period: 1986-2015

tcwind v0 hist-rcp85

\[ V_{\text{max}, 3-\text{sec}} \geq 216 \text{ kt} \]

Annual Exceedance Probability of a 3-sec Wind Gust \( \geq 216 \) kt
Current vs. Future: Category 1
Category 1 Risk

Period: 1986-2015

tcwind v0 hist-rcp85

\( V_{\text{max}, 3\text{-sec}} \geq 79 \text{ kt} \)

Annual Exceedance Probability of a 3-sec Wind Gust \( \geq 79 \text{ kt} \)
Category 1 Risk

Period: 2071-2100
tcwind v0 rcp85

\( V_{\text{max, 3-sec}} \geq 79 \text{ kt} \)

Annual Exceedance Probability of a 3-sec Wind Gust \( \geq 79 \text{ kt} \)
Current vs. Future: Category 2
Category 2 Risk

Period: 1986-2015
tcwind v0 hist-rcp85

$V_{\text{max, 3-sec}} \geq 102 \text{ kt}$

Annual Exceedance Probability of a 3-sec Wind Gust $\geq 102 \text{ kt}$
Category 2 Risk

Period: 2071-2100
tcwind v0 rcp85

V_{\text{max, 3-sec}} \geq 102 \text{ kt}

Annual Exceedance Probability of a 3-sec Wind Gust \geq 102 \text{ kt}
Current vs. Future: Category 3
Category 3 Risk

Period: 1986-2015
tcwind v0 hist-rcp85

$V_{\text{max}}, 3\text{-sec} \geq 118 \text{ kt}$

Annual Exceedance Probability of a 3-sec Wind Gust $\geq 118 \text{ kt}$
Category 3 Risk

Period: 2071-2100
tcwind v0 rcp85

$V_{\text{max, 3-sec}} \geq 118 \text{ kt}$

Annual Exceedance Probability of a 3-sec Wind Gust $\geq 118 \text{ kt}$
Current vs. Future: Category 4
Category 4 Risk

Period: 1986-2015
tcwind v0 hist-rcp85

$V_{\text{max, 3-sec}} \geq 139 \text{ kt}$

Annual Exceedance Probability of a 3-sec Wind Gust $\geq 139 \text{ kt}$
Category 4 Risk

Period: 2071-2100
tcwind v0 rcp85

$V_{\text{max, 3-sec}} \geq 139 \text{ kt}$

Annual Exceedance Probability of a 3-sec Wind Gust $\geq 139$ kt
Current vs. Future: Category 5
Category 5 Risk

Period: 1986-2015
tcwind v0 hist-rcp85

$V_{\text{max, 3-sec}} \geq 167$ kt

Annual Exceedance Probability of a 3-sec Wind Gust $\geq 167$ kt
Category 5 Risk

Period: 2071-2100
tcwind v0 rcp85

$V_{\text{max}, \text{3-sec}} \geq 167 \text{ kt}$

Annual Exceedance Probability of a 3-sec Wind Gust $\geq 167 \text{ kt}$
Current vs. Future: Category 6
Category "6" Risk

Period: 1986-2015

tcwind v0 hist-rcp85

$V_{\text{max}, 3\text{-sec}} \geq 192 \text{ kt}$

Annual Exceedance Probability of a 3-sec Wind Gust $\geq 192 \text{ kt}$
Category "6" Risk

Period: 2071-2100
tcwind v0 rcp85

$V_{\text{max, 3-sec}} \geq 192 \text{ kt}$

Annual Exceedance Probability of a 3-sec Wind Gust $\geq 192 \text{ kt}$
Current vs. Future: Category 7
Category "7" Risk

Period: 1986-2015
tcwind v0 hist-rcp85

Annual Exceedance Probability of a 3-sec Wind Gust ≥ 216 kt
Category "7" Risk

Period: 2071-2100  
tcwind v0 rcp85  
$V_{\text{max}, \text{3-sec}} \geq 216 \text{ kt}$

Annual Exceedance Probability of a 3-sec Wind Gust $\geq 216 \text{ kt}$
Future Annual Exceedance Probability (10-y Return Period)

Period: 2071-2100
tcwind v0 rcp85

Change in Frequency of Events

0.1X -70% -60% -50% -40% -30% -20% -10% NC +10% +20% +30% +50% 1X 3X 5X 9X

0.01 0.03 0.04 0.05 0.06 0.07 0.08 0.09 0.10 0.11 0.12 0.13 0.15 0.20 0.30 0.50 0.90

Future Annual Exceedance Probability of a 3-sec Wind Gust (10-y RP)
Future Annual Exceedance Probability (100-y Return Period)

Period: 2071-2100
tcwind v0 rcp85

Change in Frequency of Events

Future Annual Exceedance Probability of a 3-sec Wind Gust (100-y RP)
Summary

• Many different approaches to assessing TC wind hazard
• Synthetic tracks / parametric models probably offer the most quantitative results although there will still be local biases
• For basin-wide statistics, a statistical approach may be best
• For questions of future climate change, there are many uncertainties
Summary, cont’d

• Intensity
  ▪ Likely to increase in many of the global TC basins with significant interbasin variability
  ▪ The most intense TCs are likely to become more intense

• Frequency
  ▪ Likely to decrease somewhat or stay the same with significant interbasin variability

• Rainfall
  ▪ Likely to increase substantially
Summary, cont’d

• **Storm surge inundation**
  - May increase somewhat with increasing intensity, but sea level rise will likely result in substantially worse inundation

• **Track**
  - There is possibility that TC tracks will shift further poleward, however this is quite controversial
  - Such changes could result in drastic increases in TC hazard which currently have low risk
Questions

All North Atlantic and Eastern North Pacific tropical cyclones (from Ethan Gibney, NHC/WFO SGX)